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Year: 2013

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DOI: <https://doi.org/10.1051/epjconf/20136004003>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-92167>

Conference or Workshop Item

Published Version

Originally published at:

Elsasser, Christian (2013). Rare Decays. In: LHCP 2013 – Large Hadron Collider Physics 2013, Barcelona, 13 May 2013 - 18 May 2013. EDP Sciences, 04003.

DOI: <https://doi.org/10.1051/epjconf/20136004003>

## Rare Decays

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**Abstract.** This review presents recent results on key measurements of rare  $B$  and  $\tau$  decays performed at the LHC and the TeVatron. Its main focus lies on recent measurements of the decay  $B_{(s)}^0 \rightarrow \mu^+\mu^-$  at the two colliders and of angular observables for the decay  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  at the LHC experiments ATLAS, CMS and LHCb. Furthermore, the branching fraction measurement at low dilepton masses in the channel  $B^0 \rightarrow K^{*0}e^+e^-$  from LHCb and results on the decay  $B^\pm \rightarrow \pi^\pm\mu^+\mu^-$  as well as on lepton-flavour- and baryon-number-violating rare decays of  $\tau$  leptons are discussed.

### 1 Introduction

The GIM-Mechanism [1] forbids processes involving Flavour-Changing Neutral Currents (FCNC) at tree level in the Standard Model (SM). Therefore decays of hadrons involving  $b \rightarrow s$ ,  $b \rightarrow d$ ,  $s \rightarrow d$  or  $c \rightarrow u$  transitions are only allowed via box or penguin diagrams leading to a large suppression in the SM. This means that contributions from new physics (NP) involving “new” virtual particles might be of the same order of magnitude than the one from SM making these decays possible places to search for effects from NP.

Due to the full spectrum of  $B$  and  $D$  hadrons produced at hadron colliders there is a large variety of decays to study FCNC (e.g. for  $\Delta B = \pm 1$   $B^0 \rightarrow K^{*0}\gamma$ ,  $B_s^0 \rightarrow \mu^+\mu^-$ ,  $\Lambda_b^0 \rightarrow \Lambda^0\mu^+\mu^-$ ) with a rich phenomenology of observables which can be modified by NP contributions (e.g.  $B^0 \rightarrow K^{*0}\gamma$ :  $\mathcal{A}_{CP}$ ,  $B_s^0 \rightarrow \mu^+\mu^-$ : branching fraction,  $\Lambda_b^0 \rightarrow \Lambda^0\mu^+\mu^-$ : differential branching fraction).

Processes of FCNC can be described by an effective Hamiltonian [2], e.g. for the  $b \rightarrow s$  transition

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}\sum_i(C_i\mathcal{O}_i + C_i'\mathcal{O}_i') + \text{h.c.} \quad (1)$$

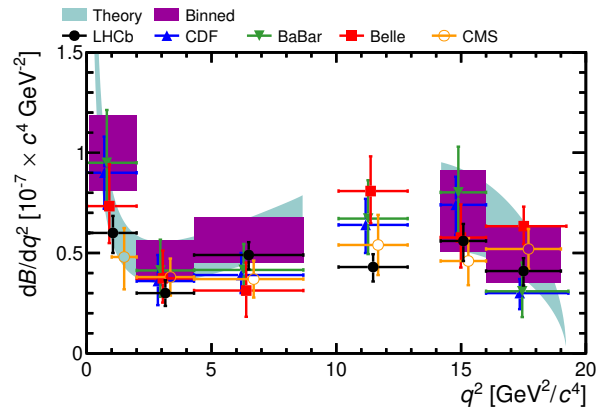
where  $\mathcal{O}_i^{(\prime)}$  are the local operators describing the long distance interaction while the Wilson coefficients  $C_i^{(\prime)}$  describe the short distance couplings.

Effects of NP can either modify the Wilson coefficients or lead to contributions from additional operators not present in the SM.

### 2 The Decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$

The decay  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  is sensitive to the Wilson coefficients  $C_9^{(\prime)}$  and  $C_{10}^{(\prime)}$  assigned to the semileptonic opera-

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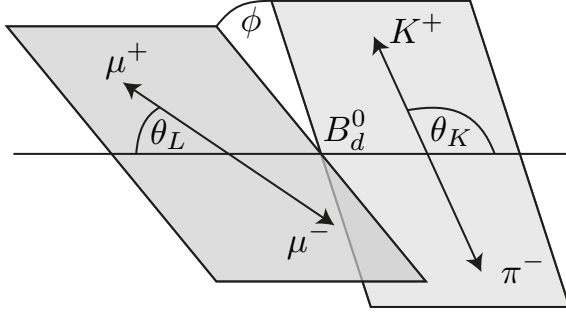
**Figure 1.** The differential branching fraction  $d\mathcal{B}/dq^2$  for the decay  $B^0 \rightarrow K^{*0}\mu^+\mu^-$  as a function of the invariant dimuon mass squared  $q^2$ . The coloured error bars represent the latest measurements from LHC, TeVatron and  $B$  factory experiments while the SM prediction [10] and its average over the experimental bins are shown by the blue band and the purple rectangles, respectively.

tors. In addition the decay is at low invariant dimuon mass squared ( $q^2$ ) also sensitive to  $C_7^{(\prime)}$  assigned to the magnetic operator as  $q^2$  is approaching the photon pole.

The branching fraction of the decay has been measured by several experiments [3–5] and good agreement with the SM prediction [6–9] has been found. Nevertheless NP might affect the differential branching fraction  $d\mathcal{B}/dq^2$  and the angular distribution of the final state particles.

The  $B$  factories as well as CDF have measured the differential branching fraction in the past [11–13]. In spring 2013 LHCb [14] and CMS [15] published results based on their full 2011 data sets of  $1.0 \text{ fb}^{-1}$  and  $5.2 \text{ fb}^{-1}$ , respectively.

The analyses have been done by fitting the invariant mass distribution of the  $B^0$  candidates in bins of  $q^2$ . The  $q^2$



**Figure 2.** Helicity angle definition of  $\theta_l$ ,  $\theta_K$  and  $\phi$  in  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ .  $\theta_l$  is the angle between the flight direction of  $B^0$  and the decay line of the muons in the dimuon rest frame and  $\theta_K$  the one between the flight direction of  $B^0$  and the flight direction of the charged kaon in the  $K^{*0}$  rest frame while  $\phi$  is the angle between the dimuon and  $K^{*0}$  decay plane.

regions at  $q^2 = 9.5 \text{ GeV}^2/c^4$  and  $13.5 \text{ GeV}^2/c^4$  corresponding to the  $J/\psi$  and  $\psi(2S)$  resonances are excluded. The number of signal events has been normalized to the decay channel  $B^0 \rightarrow J/\psi K^{*0}$ . This is also the source of the largest systematic uncertainty. A possible  $K^+ \pi^-$  S-wave contamination from  $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$  has been only taken into account as a systematic uncertainty by ATLAS and LHCb. CMS incorporates it into the fit. The measurements show good agreement with the SM prediction [10]<sup>1</sup> (cf. Fig. 1). The prediction has large uncertainties induced by the form factor calculation. This leads to a reduced sensitivity to NP effects.

The angular distribution of the decay can be fully described by the three helicity angles  $\theta_l$ ,  $\theta_K$  and  $\phi$  (defined in Fig. 2) as well as  $q^2$ . An angular analysis of the decay gives access to several observables with small theoretical uncertainties and possible large effects from NP [17]. The two most prominent ones, measured by all three LHC experiments<sup>2</sup> are the fraction of longitudinal polarized  $K^{*0}$  mesons,  $F_L$ , and the forward-backward asymmetry of the leptons with respect to the  $B^0$  flight direction,  $A_{FB}$ , which can be determined through the double differential decay rates integrated over  $\theta_l$  and  $\phi$

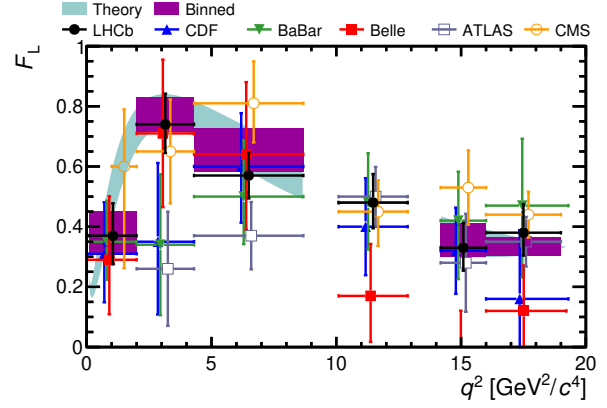
$$\frac{1}{\Gamma} \frac{d^2\Gamma}{dq^2 d\cos\theta_l} = \frac{3}{4} F_L(q^2) (1 - \cos^2\theta_l) + \frac{3}{8} (1 - F_L(q^2)) (1 + \cos^2\theta_l) + A_{FB}(q^2) \cos\theta_l \quad (2)$$

and integrated over  $\theta_K$  and  $\phi$ ,

$$\frac{1}{\Gamma} \frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2} F_L(q^2) \cos^2\theta_K + \frac{3}{4} (1 - F_L(q^2)) (1 - \cos^2\theta_K). \quad (3)$$

<sup>1</sup>An alternative set of predictions consistent with the SM, averaged over each  $q^2$  bin, has been recently published in Ref. [16].

<sup>2</sup>LHCb has also measured other observables including the theoretically very clean transverse asymmetries  $A_T^2$  and  $A_T^{\text{Re}}$  [17].



**Figure 3.** The fraction,  $F_L$ , of longitudinal polarized  $K^{*0}$  mesons in the decay  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  as a function of the invariant dimuon mass squared,  $q^2$ , measured by LHC and TeVatron experiments as well as the  $B$  factories. The SM prediction [10] and its average over the experimental bins are shown by the blue band and the purple rectangles, respectively.

Recent measurements of LHCb [14], CMS [15] and ATLAS using their 2011 data set of  $4.9 \text{ fb}^{-1}$  [18] are based on a simultaneous fit of the  $B^0$  candidate mass distribution as well as the  $\cos\theta_K$  and  $\cos\theta_l$  distributions<sup>3</sup> in bins of  $q^2$ . Fig. 3 and 4 show the measured values for  $F_L$  and  $A_{FB}$  from the three LHC experiments as well as previous measurements from the  $B$  factories [11, 12] and CDF [13].

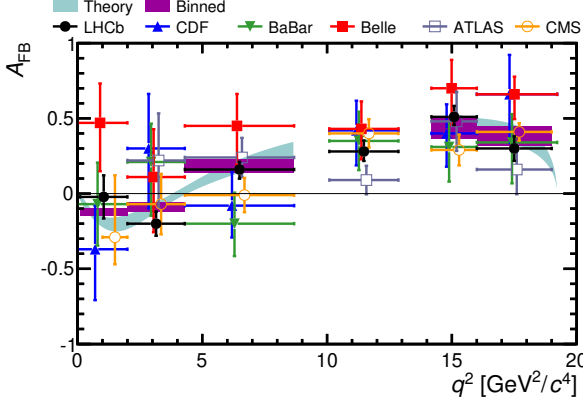
In case of  $F_L$ , no significant deviation from the SM prediction [10] has been observed. Especially the most precise measurements from LHCb and CMS show in all bins of  $q^2$  a good agreement with respect to the SM prediction.

A similar situation is present in  $A_{FB}$ : No experiment sees a significant deviation from the SM prediction. CMS and LHCb show particularly in the low  $q^2$  region a good agreement with the theoretical prediction and therefore clearly disfavor a possible deviation from SM predictions which could not have been ruled out by BELLE in this region. In addition LHCb measured for the first time the zero-crossing point  $q_0^2$  of  $A_{FB}$ . The result,  $(4.9 \pm 0.9) \text{ GeV}^2/c^4$  [14] is in good agreement with SM predictions of  $3.9 - 4.3 \text{ GeV}^2/c^4$  [19–21]. The quoted uncertainty is only the statistical one as the systematical uncertainty on the measured value of  $q_0^2$  is so far negligible in comparison to the statistical one. Note, that the existence of a zero-crossing point fixes the sign of  $C_7$  relative to the sign of  $C_9$  [22].

<sup>3</sup>LHCb also fits the  $\hat{\phi}$  distribution where

$$\hat{\phi} = \begin{cases} \phi + \pi & \text{if } \phi < 0 \\ \phi & \text{else.} \end{cases}$$

which leads to a better sensitivity and allows to determine additional observables.



**Figure 4.** The lepton forward-backward asymmetry,  $A_{FB}$ , with respect to the flight direction of the  $B^0$  meson as a function of the invariant dimuon mass squared,  $q^2$ , measured by LHC and TeVatron experiments as well as  $B$  factories. The SM prediction [10] and its average over the experimental bins are shown by the blue band and the purple rectangles, respectively.

### 3 The Decay $B^0 \rightarrow K^{*0} e^+ e^-$

Similar measurements – although experimentally more challenging – can be performed with electrons instead of muons in the final state. The channel  $B^0 \rightarrow K^{*0} e^+ e^-$  can be used to probe the very low  $q^2$  region due to the smaller mass of the final state leptons. Therefore this channel is more sensitive to the photon coupling described by  $C_7^{(\prime)}$ . As a first step toward a full angular analysis, LHCb has measured [23] based on the 2011 data set the branching fraction at low  $q^2$  with  $\sqrt{q^2} = m_{ee} \in [30, 1000]$  MeV/c<sup>2</sup>. The number of signal events is normalized using the decay channel  $B^0 \rightarrow J/\psi(\rightarrow e^+ e^-) K^{*0}$ . The measured branching fraction is:

$$\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)_{[30,1000]} = (3.1^{+0.9}_{-0.8}(\text{stat.})^{+0.3}_{-0.4}(\text{syst.})) \times 10^{-7}.$$

The dominating systematic uncertainty is due to the uncertainty on the branching fraction of the normalization channel. There is also a 2.5 % uncertainty due to possible contamination from the decay  $B^0 \rightarrow K^{*0} \gamma$  with photon conversion.

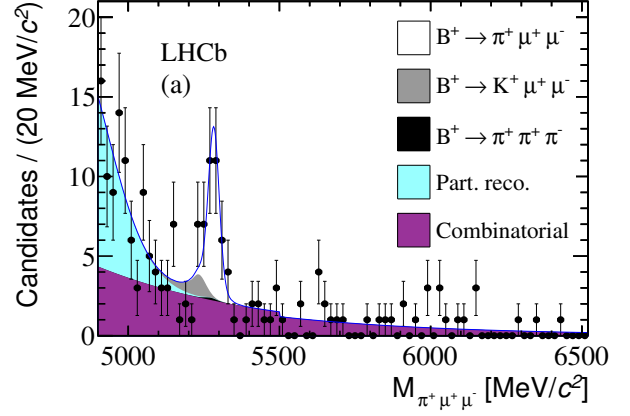
### 4 The Decay $B^\pm \rightarrow \pi^\pm \mu^+ \mu^-$

The decay  $B^\pm \rightarrow \pi^\pm \mu^+ \mu^-$  involves a  $b \rightarrow d$  transition and can therefore be used to test the flavour structure of possible NP models.

Under the assumption of Minimal Flavour Violation (MFV), i.e. a similar flavour structure as in the SM, the ratio of the branching fractions between  $B^\pm \rightarrow \pi^\pm \mu^+ \mu^-$  and  $B^\pm \rightarrow K^\pm \mu^+ \mu^-$  is

$$\frac{\mathcal{B}(B^\pm \rightarrow \pi^\pm \mu^+ \mu^-)}{\mathcal{B}(B^\pm \rightarrow K^\pm \mu^+ \mu^-)} = |V_{td}/V_{ts}|^2 \cdot f^2 \quad (4)$$

where  $f$  covers differences in the form factors of the two decay channels.



**Figure 5.** The invariant mass distribution of the  $B^\pm \rightarrow \mu^+ \mu^- \pi^\pm$  candidates. Beside background coming from combinatorics as well as partial reconstruction also background coming from mis-identification of the pion or the two muons are considered in the signal yield fit.

LHCb has measured this ratio based on the full 2011 data sample [24]. Fig. 5 shows the  $\pi\mu\mu$  invariant mass distribution of the candidates selected by a boosted decision tree (BDT). The signal yield has been extracted by a unbinned maximum-likelihood fit taking into account combinatorial background as well as backgrounds from partially reconstructed decays and mis-identified final state particles. The resulting ratio has been

$$\frac{\mathcal{B}(B^\pm \rightarrow \pi^\pm \mu^+ \mu^-)}{\mathcal{B}(B^\pm \rightarrow K^\pm \mu^+ \mu^-)} = 0.053 \pm 0.014(\text{stat.}) \pm 0.001(\text{syst.}) \quad (5)$$

translating into

$$|V_{td}/V_{ts}| = 0.266 \pm 0.035(\text{stat.}) \pm 0.003(\text{syst.}) \quad (6)$$

using  $f = 0.87$  [25] and neglected the uncertainty on  $f$  in calculating the systematical uncertainty on the CKM matrix elements ratio. No large enhancement of  $b \rightarrow d$  is observed as the extracted ratio does not significantly deviate from the World average of  $|V_{td}/V_{ts}| = 0.211 \pm 0.001 \pm 0.006$  [26] dominated by the ratio of the measurements of  $\Delta m_d$  and  $\Delta m_s$ .

### 5 The Decays $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

The very rare decays  $B_{(s)}^0 \rightarrow \mu^+ \mu^-$  are in addition to the GIM suppression also suppressed by helicity in the SM. Therefore they are particularly sensitive to possible NP contributions in the scalar and pseudo-scalar sector, i.e. to the Wilson coefficients  $C_{S,P}^{(\prime)}$  assigned to the scalar and pseudo-scalar operator. Thus the branching fraction measurements can test models with an extended Higgs sector. The predicted values for the branching fractions are

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) &= (3.25 \pm 0.17) \times 10^{-9} \\ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &= (1.07 \pm 0.10) \times 10^{-10} \end{aligned}$$

where both values are evaluated for a decay time  $t = 0$  of the meson [27]. This fact has to be taken into account for the decay  $B_s^0 \rightarrow \mu^+\mu^-$  as the  $B_s^0$  meson has a finite width difference  $\Delta\Gamma_s$  which leads to a modified branching fraction of

$$\begin{aligned} \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)_{(t)} &= \frac{1 + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \cdot \Delta\Gamma_s/2\Gamma_s}{1 - (\Delta\Gamma_s/2\Gamma_s)^2} \cdot \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) \\ &= (3.56 \pm 0.18) \times 10^{-9} \end{aligned}$$

when averaging over all decay time values [28].  $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$  is an observable sensitive to NP. It can take values between  $-1$  and  $+1$  with  $\mathcal{A}_{\Delta\Gamma}^{\mu\mu;SM} = +1$ . As all analyses of  $B_s^0 \rightarrow \mu^+\mu^-$  have so far been performed in a time-integrated way, one has to compare the results with this modified prediction. The TeVatron experiments CDF and D0 published at the beginning of 2013 results based on the full data samples collected in the TeVatron run II [29, 30]. Both experiments use multivariate classifiers as well as the invariant dimuon mass to separate signal and background and normalize the signal yield using the decay  $B^\pm \rightarrow J/\psi K^\pm$ . D0 measures an upper limit of

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 15 \times 10^{-9} @ 95 \% \text{ C.L.}$$

while CDF – analyzing events where both muons fly into the central region of the detector (CC) or one muon flying into the forward direction (CF) separately – sees an excess in the CC channel translating into a double-sided limit of

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) \in [0.8, 34] \times 10^{-9} @ 95 \% \text{ C.L.},$$

which is compatible with the SM prediction.

The latest results from ATLAS [31] and CMS [32] are based on  $2.4 \text{ fb}^{-1}$  and  $5.0 \text{ fb}^{-1}$  of 2011 data, respectively. ATLAS has used a similar approach in analyzing the decay as the TeVatron experiments and determined an upper limit of

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 22 \times 10^{-9} @ 95 \% \text{ C.L.}$$

while CMS performs a cut based analysis leading to an upper limit of

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 7.7 \times 10^{-9} @ 95 \% \text{ C.L.}$$

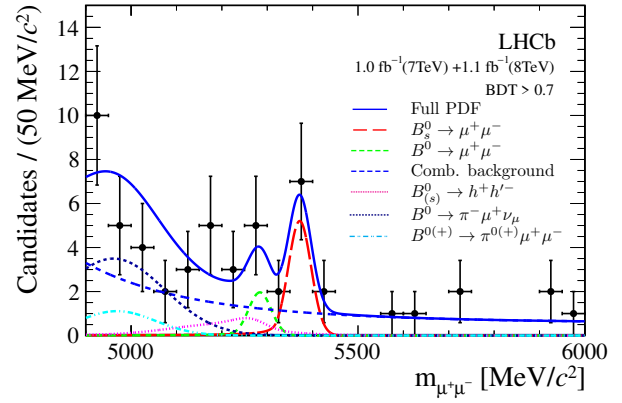
The most powerful result on this decay comes from LHCb based on a combined analysis of  $1.0 \text{ fb}^{-1}$  of 2011 data and  $1.1 \text{ fb}^{-1}$  of 2012 data [33]. The measurement is based on a BDT and the invariant dimuon mass to separate signal and background and uses the decays  $B^\pm \rightarrow J/\psi K^\pm$  and  $B^0 \rightarrow K^\pm \pi^\mp$  to normalize the observed number of signal events.

In this analysis LHCb has seen for the first time an evidence of the decay  $B_s^0 \rightarrow \mu^+\mu^-$  as there has been a  $3.5\sigma$  deviation from the background only hypothesis.

Furthermore, LHCb has measured the branching fraction by fitting the invariant dimuon mass distribution simultaneously in eight bins of the BDT classifier (cf. Fig. 6).

This leads to

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.2_{-1.2}^{+1.4}(\text{stat})_{-0.3}^{+0.5}(\text{syst})) \times 10^{-9} \quad (7)$$



**Figure 6.** The invariant dimuon mass distribution for very signal-like  $B_{(s)}^0 \rightarrow \mu^+\mu^-$  candidates together with the signal and background contributions included in the branching fraction fit.

in good agreement with the SM prediction.

Fig. 7 shows the most recent results on the  $B_s^0 \rightarrow \mu^+\mu^-$  branching fraction compared to SM predictions. All recent measurements are in agreement with the SM. The result from LHCb gives strong constraints on possible NP in the scalar and pseudo-scalar sector. This means also that the decay starts to be sensitive to the Wilson coefficient  $C_{10}^{(\prime)}$  associated to the axial-vector operator, which is the only one allowed in the SM.

In the case of  $B^0 \rightarrow \mu^+\mu^-$  no significant excess over background has been seen by CDF, CMS and LHCb which have analyzed this decay. The most stringent upper limit has been observed by LHCb using  $1.0 \text{ fb}^{-1}$  of 2011 data and  $1.1 \text{ fb}^{-1}$  of 2012 data [33], resulting in

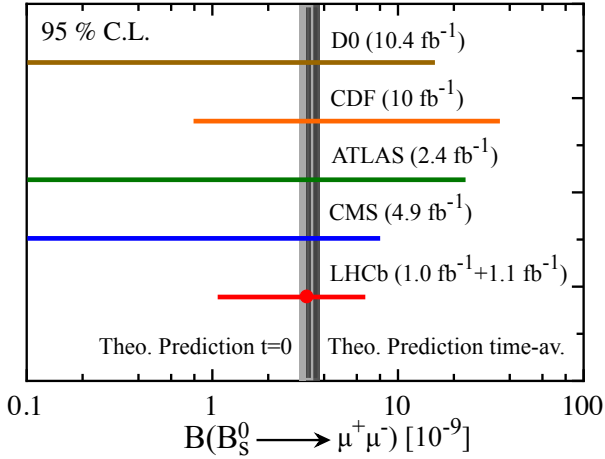
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10} @ 95 \% \text{ C.L.}$$

## 6 Lepton Flavour and Baryon Number Violating Decays

Besides hadronic rare decays, LHCb also studies rare decays of leptons, including searches for the lepton violating decay  $\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-$ . In the SM this decay is only allowed via neutrino oscillation resulting in a predicted branching fraction of the order of  $10^{-54}$  [34]. But many extensions of the SM, e.g. supersymmetric models, allow flavour violation in the charged lepton sector and therefore predict a branching fraction of the order of  $10^{-10}$  to  $10^{-8}$  [35] which is in reach of LHCb. So far, the world's best upper limit has been set by BELLE with  $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-) < 2.1 \times 10^{-8} @ 90 \% \text{ C.L.}$  [36].

The decay  $\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-$  has been studied in LHCb using the  $1.0 \text{ fb}^{-1}$  data sample collected in 2011. The analysis follows a similar path as the search for  $B_{(s)}^0 \rightarrow \mu^+\mu^-$  with usage of multivariate classifiers based on particle identification requirements as well as topological and kinematical properties of a three-body decay and the invariant tri-muon mass.





**Figure 7.** Summary plot of the most recent branching fraction measurements of  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$  at LHC and TeVatron. All measurements are in perfect agreement with the SM prediction (light-gray: prediction for proper time  $t = 0$ , dark-gray: time-averaged prediction)

The signal yield is normalized using the decay  $D_s^\pm \rightarrow \phi(\rightarrow \mu^+ \mu^-) \pi^\pm$ . The upper limit is extracted using a binned  $CL_s$  method [37] and gives an upper limit of [38]

$$\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \mu^+ \mu^-) < 8.0 \times 10^{-8} @ 90 \% \text{ C.L.}$$

LHCb has also set in a similar manner for the first time direct limits on the branching fractions for the baryon number violating decays  $\tau^+ \rightarrow p \mu^+ \mu^-$  and  $\tau^+ \rightarrow \bar{p} \mu^+ \mu^+$  [38]

$$\mathcal{B}(\tau^+ \rightarrow p \mu^+ \mu^-) < 3.3 \times 10^{-7} @ 90 \% \text{ C.L.}$$

$$\mathcal{B}(\tau^+ \rightarrow \bar{p} \mu^+ \mu^+) < 4.4 \times 10^{-7} @ 90 \% \text{ C.L.}$$

## 7 Summary

In recent months many interesting measurements in the field of rare decays have been performed at hadron colliders. So far, there is no significant disagreement between the SM predictions and the measurements. This leads to tight constraints on possible NP models.

The data samples collected at LHC in the 2012 run have been only partially analyzed. Especially the measurements based on these data samples of  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  as well as of radiative rare decays like  $B^0 \rightarrow K^{*0} \gamma$  will be interesting probes of possible effects beyond the SM.

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